Optimization of the Relay Selection Scheme in Cooperative Retransmission Networks

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***Abstract*—While the benefits of cooperative diversity have been well studied in the literature, cooperative MAC protocol design has attracted more and more attention recently. In single-relay Cooperative Automatic Repeat reQuest (C-ARQ) protocol, the best relay node is selected in a distributed manner by relays using different backoff time before packet retransmission. However, this relay selection scheme does not work efficiently in a dense network scenario, due to high collision probability among different contending relays. In this paper, we propose an optimized relay selection scheme to maximize the system throughput by reducing the collision probability. The performance improvement in terms of throughput and packet delivery ratio by the proposed optimal relay selection scheme is verified by simulations.**

I. INTRODUCTION

Cooperative communications are proposed as a distributed way to achieve space diversity via distributed terminals. The theory behind cooperation has been studied in depth, and significant improvement of system performance has been demonstrated in terms of throughput, network coverage and energy efficiency [1].

More and more attention has recently been paid to cooperative Medium Access Control (MAC) design in distributed wireless networks [2]- [5]. Among them, a Cooperative Automatic Repeat reQuest protocol (C-ARQ) has been is proposed in [8] to deal with the three key issues on MAC layer. In single-relay C-ARQ, the relay nodes with successful reception of the direct transmission from source to destination will backoff different lengths of time before data retransmission, according to their instantaneous relay channel quality. Therefore, the relay node with best relay channel quality will be selected automatically to forward the data packet. The C-ARQ scheme can provide high performance enhancement compared with the non-cooperative scheme in a sparse network. However, Its performance would be remarkably degraded in dense networks because of the high collision probability in its relay selection procedure.

In fact, collision among relays is a common problem that exists in a category of distributed path selection protocols based on different lengths of backoff time [6] before transmission. The collision happens when more than one relay node have the same shortest backoff time, and hence transmit simultaneously. For example, the CoopMAC-Aggregation protocol in [7] is proposed for cooperative communication in Wireless Local Area Networks (WLANs). There is a priority round in its helper selection mechanism, where different slots are allotted to different helper groups according to the effective data transmission rate on each relay link. In this case, the collision caused by multiple relay nodes with similar effective data rates and hence the same slottime also leads to serious impairment of the protocol performance in dense networks.

Based on the above discussion, an optimal mapping scheme from relay channel condition to backoff time is required to reduce the collision probability. Therefore, an optimal relay selection scheme is proposed in this paper to improve the C-ARQ performance in a dense network. Furthermore, the optimal mapping scheme here applies to the above mentioned protocols with similar problems. Hence, the optimization solution study is of great significance. Analysis and simulations are conducted to evaluate the performance enhancement of the proposed optimal scheme, in terms of network throughput and packet delivery ratio.

The rest of the paper is organized as follows. The system model is described in Sec. II. After that, the cooperative protocol is introduced in Sec. III. The optimization problem statement of the relay selection scheme is derived in Sec. IV, and the scheme performance is evaluated through simulations in Sec. V. Finally, the paper is concluded in Sec. VI.

II. SYSTEM MODEL AND ASSUMPTIONS

The network shown in Fig. 1 is taken as an example to illustrate the network topology and cooperation scenario. The network consists of a source node, S, a destination node, D, and several potential relay nodes, R_1, R_2, ..., R_n, randomly distributed around D [1].

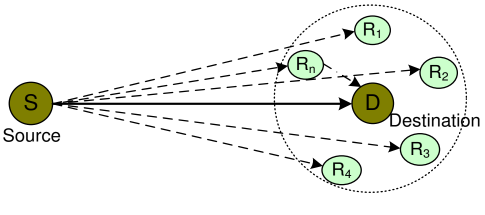

Fig. 1. System Model for Cooperative Transmission.

Each direct transmission starts from S, with the intended destination as D. If the direct transmission fails, the relay node which has received the packet successfully and has the best relay channel quality to D will be selected to forward the packet to D, following the cooperative retransmission protocol.

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[1] This network topology is based on our previous work [9], where we have demonstrated that it is more energy efficient to use relay nodes close to the destination in the context of cooperative retransmission network.

In this model, it is assumed that all nodes can hear each other. The distance between any relay node and D is negligible compared to the distance between S and D. The channels between every transmission pair, i.e., between S and D, S and each relay node R$_i$, as well as R$_i$ and D, are assumed to be independent of each other, hence full spatial diversity can be achieved by data retransmission over another/other channel(s). Moreover, we assume the channels are strongly temporally correlated, i.e., consecutive packets on the same channel are subjected to the same channel fading condition and hence identical packet error rate.

III. COOPERATIVE MAC PROTOCOL DESCRIPTION

The C-ARQ protocol is proposed based on the Distributed Coordination Function (DCF) scheme in WLANs, to deal with the three key issues on MAC layer, i.e., when to cooperate, whom to cooperate with and how to protect cooperative transmissions [8]. In this section, we first summarize the C-ARQ MAC protocol, and then introduce its relay selection algorithm in details in the second subsection.

A. Cooperative Automatic Repeat Request Scheme

The C-ARQ protocol procedure consists of two phases: direct transmission and cooperative retransmission. The co-operative retransmission only happens when the first direct transmission fails. It is briefly presented in the following about how the protocol works. More details can be found in [8].

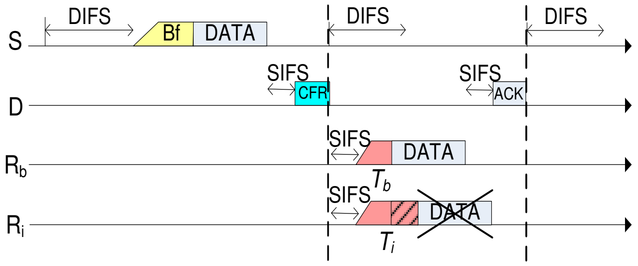

Fig. 2. C-ARQ Basic Access Scheme.

As the first step, S sends out a DATA packet to its destination D following the original DCF basic access scheme. If and only if the data packet is received erroneously at D, D will broadcast a Call For Cooperation (CFC) packet to invite other nodes in the network to operate as relay nodes and at the same time to provide them the opportunity of measuring their respective relay channel quality. Only relay nodes that have decoded the packet sent by S correctly become relay candidates. According to the relay selection algorithm, the relay candidate with the best relay channel quality R$_b$, will first get channel access and forward its received packet to the destination. After detecting the data packet from R$_b$ on the channel, the other relay candidates will withdraw from the cooperation contention and discard their received packets. If D decodes the packet correctly after the best-relay-channel retransmission, D will return an ACK packet to S. Otherwise, the cooperative transmission fails. In this case, S will get access to the channel again after DIFS interval.

The message exchange sequence of the C-ARQ scheme with a successful cooperative retransmission is illustrated in Fig. 2.

B. Relay Selection Algorithm

The relay nodes in C-ARQ are selected in a distributed manner by using the instantaneous channel condition obtained through the CFC packet sent from D. After the cooperative phase starts, each relay candidate gets its backoff time of T_i according to its own relay channel condition.

1) backoff time function: In C-ARQ, the backoff time, T_i is defined as a function:

$$T_i = \left\lfloor \frac{SNR_{low}}{SNR_i} \frac{T_{up}}{slottime} \right\rfloor, \quad i = 1, 2, \ldots, n \tag{1}$$

where SNR_i is the Signal-to-Noise Ratio (SNR) value in dB of the CFC packet received at R_i; SNR_{low} is the threshold of SNR_i for R_i to participate in cooperative retransmission; and n is the number of the relay nodes in the network. The value of SNR_{low} can be determined according to the specified Modulation and Coding Schemes (MCSs) at the physical layer. T_{up} in Eq. (1) is the upper bound of the backoff time for relay candidates. T_{up} in the basic C-ARQ scheme is set to be (DIFS-SIFS), in order to guarantee that the cooperative retransmission will not be interrupted by other nodes in the network. The granularity of T_i is specified to be *slottime* of the system in order to cover the propagation delay in the network.

2) backoff time look-up table: The mapping from SNR_i to T_i can also be implemented through a look-up table, as shown in Table I.

TABLE I
MAPPING FROM SNR TO BACKOFF TIME.

SNR_i	$[\vartheta_1, \infty)$	$[\vartheta_2, \vartheta_1)$	$[\vartheta_3, ...$	$(\vartheta_m, \vartheta_{m-1})$
Backoff time T_i	first slot	second slot	...	$DIFS - SIFS$

In Table. 1, $\vartheta_j, j = 1, 2, ..., m$ are the threshold values of SNR_i to have different backoff time, and $\vartheta_1 \geq \vartheta_2 \geq ... \geq \vartheta_m$. ϑ_m is the threshold value for the relay candidate to cooperate. Each relay candidate gets its backoff time T_i by looking up the above table using its measured SNR value of the CFC packet as index. It is obvious that the relay with highest SNR_i will get the first time slot and hence to transmit first.

The number of intervals divided among the SNR values in Table. 1, m is determined by the durations of (DIFS-SIFS) and slottime. The longest backoff time available for the relays is set to $\left\lfloor \frac{DIFS-SIFS}{slottime} \right\rfloor$ slots to give priority to cooperative retransmission. The boundaries involved in this table, $\vartheta_i, i = 1, 2..., m$, can be optimized to minimize the probability of two or more relays with the same shortest backoff time. For instance, in a network with 802.11g standard, the longest backoff time is three time slots. Hence, two threshold values, ϑ_1 and ϑ_2, need to be optimized. The optimization solution is dependent on given network scenarios, such as the wireless channel quality and the density of the relay nodes.

IV. OPTIMIZATION PROBLEM STATEMENT

Let d denote the distance between the source node and a receiving node. We assume an average path loss that is proportional to d^a where a is the path loss coefficient. For brevity, we assume a Rayleigh fading channel with additive white Gaussian noise (AWGN) on top of path loss, although our analysis can be extended to other fading channels such as Rician or Nakagami.

The average received SNR at the receiver can be written as

$$\overline{\gamma} = \frac{GP_T(1-\alpha)}{d^\alpha N_0 W}, \tag{2}$$

where P_T is the power consumption during RF transmission; $(1-\alpha)$ accounts for the efficiency of the RF power amplifier, W is bandwidth in Hertz available for transmission; N_0 is the spectral power density of the Gaussian white noise at the receiver, and G is a constant that is defined by the signal frequency, antenna gains, and other parameters.

The instantaneous received SNR under Rayleigh fading has an exponential distribution as:

$$f(\gamma) = 1/\overline{\gamma} e^{-\gamma/\overline{\gamma}}. \tag{3}$$

Substituting $\overline{\gamma}$ in Eq. (2) into Eq. (3), we can obtain:

$$f(\gamma) = \frac{d^\alpha N_0 W}{GP_T(1-\alpha)} e^{-\frac{\gamma d^\alpha N_0 W}{GP_T(1-\alpha)}} = Cd^\alpha e^{-Cd^\alpha \gamma}, \tag{4}$$

where $C = \frac{N_0 W}{GP_T(1-\alpha)}$.

A. Average Packet Error Rate

The exact closed-form PER in AWGN channels is difficult to obtain. To simplify the analysis, we will rely on the following approximate PER expression [10]:

$$PER_n(\gamma) \approx \begin{cases} 1 & \text{if } \gamma <= \gamma_n^{th} \\ \beta_n e^{-\kappa_n \gamma}, & \text{if } \gamma > \gamma_n^{th} \end{cases} \tag{5}$$

where n is the MCS index, and γ is the signal to noise ratio at the receiver. Parameters β_n, κ_n and γ_n^{th} are dependent on the specific MCS scheme and data packet length.

Given an average SNR value, the PER performance at the receiving node averaged over Rayleigh fading is given as:

$$\begin{aligned} \overline{PER}_r(\overline{\gamma}) &= \int_0^\infty PER(\gamma) f(\gamma)\,\mathrm{d}\gamma \\ &= \frac{\beta_n}{1+\kappa_n\overline{\gamma}} e^{-\gamma_n^{th}(\kappa_n + 1/\overline{\gamma})} + \left(1 - e^{-\gamma_n^{th}/\overline{\gamma}}\right). \end{aligned} \tag{6}$$

Since all the relays nodes are close to the destination, and the distance between them is negligible compared with the distance from source to destination, we assume the average SNR is the same at all the receiving nodes in the direct transmission phase. Therefore, the *average packet error rate*, denoted as $\overline{PER}_r$, is also the same at the destination and other relay nodes. Substituting Eq. (2) into Eq. (6), we have:

$$\overline{PER}_r = \frac{\beta_n C d^\alpha}{Cd^\alpha + \kappa_n} e^{-\gamma_n^{th}(\kappa_n + Cd^\alpha)} + \left(1 - e^{-\gamma_n^{th} C d^\alpha}\right). \tag{7}$$

We assume there are N nodes in the network. Let us denote the number of nodes that correctly decode the packet as M. Since the channels from the source to different relays are independent, the event that one node successfully receives a packet is independent of others. Thus, the number of successful nodes is actually subject to a binomial distribution. The probability that M nodes correctly decode the packet is

$$P(M) = \binom{N}{M} \left[1 - \overline{PER}_r)\right]^M \left[\overline{PER}_r)\right]^{N-M}. \tag{8}$$

B. Conditional Cooperation Retransmission Probability

In the cooperative retransmission phase, the M relay nodes with successful reception of the data packet will first measure the received signal strength of the CFC packet, denoted as $\gamma_i, i = 1, 2..., M$, then contend for channel access using different backoff time T_i according to γ_i. Here, γ_i represents the instantaneous relay channel condition and follows a similar distribution function in Eq. (4). The path loss factor is neglected in this case because of the short distance between relay nodes and D. For convenience, we sort γ_i in the descending order, as $\gamma_1 \geq \gamma_2 \geq \gamma_3 ... \geq \gamma_M$.

The probability of the cooperative retransmission conditioned on the direct transmission failure, denoted as P_{coop}, is the probability that there is at least one relay node that will transmit before DIFS-SIFS timeout after an unsuccessful direct transmission. The probability P_{coop} is equal to the probability of the event that the relay node with the best relay channel quality has higher SNR value than the threshold value, ϑ_m, and hence transmit before DIFS-SIFS. Considering the independence of the channels from the source to different relays, P_{coop} can be calculated as:

$$\begin{aligned} P_{coop} &= P\{\gamma_1 > \vartheta_m\} = 1 - P\{\gamma_1 \leq \vartheta_m\} \\ &= 1 - P\{\gamma_i \leq \vartheta_m, i = 1, 2, ..., M\} \\ &= 1 - \prod_{i=1}^{M} \int_0^{\vartheta_m} Ce^{-C\gamma_i} d\gamma_i \\ &= 1 - \left(1 - e^{-C\vartheta_m}\right)^M. \end{aligned} \tag{9}$$

C. Collision Probability among Different Relays

Collision will happen when γ_1 and γ_2 have similar values, i.e., two relays have the same backoff time. Therefore, the collision probability P_{col} can be written as:

$$P_{col} = \sum_{j=1}^{m} P\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j-1})\}, \tag{10}$$

where $\vartheta_0 = \infty$. To calculate P_{col}, we have:

$$\begin{aligned} P\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j-1})\} &= P\{\gamma_1, \gamma_2 < \vartheta_{j-1}\} - P\{\gamma_1 < \vartheta_j\} \\ &\quad - P\{\vartheta_{j-1} > \gamma_1 \geq \vartheta_j\} P\{\gamma_2 < \vartheta_j | \vartheta_{j-1} > \gamma_1 \geq \vartheta_j\} \end{aligned} \tag{11}$$

In the following, we derive the three items on the right side of Eq. 11 step by step. As we defined, γ_1 and γ_2 is the maximal and the second maximal values of the received signal strengths at all the relays, respectively. Hence, $P\left\{\gamma_1, \gamma_2 \le \vartheta_j\right\}$ is equivalent to $P\left\{\gamma_1 \le \vartheta_j\right\}$, and can be obtained as:

$$\begin{aligned} P\left\{\gamma_1, \gamma_2 < \vartheta_{j-1}\right\} &= P\left\{\gamma_1 < \vartheta_{j-1}\right\} \\ &= C^M \prod_{i=1}^{M} \int_0^{\vartheta_{j-1}} e^{-C\gamma_i} d\gamma_i \\ &= \left(1 - e^{-C\vartheta_{j-1}}\right)^M . \end{aligned} \tag{12}$$

Similarly, $P\left\{\gamma_1 < \vartheta_j\right\}$ can be easily obtained.

In Eq. 11, $P\left\{\vartheta_{j-1} > \gamma_1 \ge \vartheta_j\right\} = P\left\{\gamma_1 < \vartheta_{j-1}\right\} - P\left\{\gamma_1 < \vartheta_j\right\}$. And $P\left\{\gamma_2 \le \vartheta_j | \vartheta_{j-1} > \gamma_1 \ge \vartheta_j\right\}$ can be calculated as:

$$\begin{aligned} &P\left\{\gamma_i \le \vartheta_j, i = 2..., M | \gamma_1 \ge \vartheta_j\right\} \\ &= \prod_{i=1}^{M-1} \int_0^{\vartheta_j} C e^{-C\gamma_i} d\gamma_i \\ &= \left(1 - e^{-C\vartheta_j}\right)^{M-1} . \end{aligned} \tag{13}$$

In this way, P_{col} can be expressed as a function of distance d, number of relays M, number of thresholds m, threshold values $\vartheta_j, j = 1, 2, .., m-1$. Averaging P_{col}over the distance and the number of relays leads to:

$$\begin{aligned} \overline{P}_{col}(\vartheta_j, m) &= \sum_{i=0}^{M} P(M) P_{col}(\vartheta_j, m, M, d) \\ &= \sum_{i=0}^{M} P(M) \left(\sum_{i=1}^{m} P\left\{\gamma_1, \gamma_2 \in [\vartheta_j, \vartheta_{j-1})\right\} \right) . \end{aligned} \tag{14}$$

Thus, we derived the closed-form expression of the average collision probability among different relay node, $\overline{P}_{col}$ as a function of the threshold values $\vartheta_j, j = 1, 2..., m$.

D. System Performance Analysis

The performance of the cooperative retransmission protocol is analyzed in terms of saturation throughput and Packet Delivery Rate (PDR) at the MAC layer in this subsection.

The PDR of the cooperative scheme is the sum of the packet successful rate in the direct phase and the additional successful probability in the cooperative retransmission phase. Note that in our analysis, no data corruption is assumed on the relay channels from R$_i$ to D due to short distances. That is, a failure of the cooperative retransmission is only caused by the collision among different relays due to the imperfect relay selection scheme.

$$PDR_c = 1 - \overline{PER}_r + \overline{PER}_r P_{coop} (1 - P_{col}). \tag{15}$$

The normalized system saturation throughput, denoted by η, is defined as the successfully transmitted payload bits per time unit, and can be written as:

$$\eta = \frac{E[\psi]}{E[D]}, \tag{16}$$

where $E[\psi]$ is the number of payload information bits successfully transmitted in a virtual time slot, i.e., the time interval between two consecutive packet transmissions initiated by S in this study, and $E[D]$ is the expected length of the virtual time slot. For our proposed scheme, $E[\psi]$ and $E[D]$ are expressed as follows.

$$E[\psi] = PDR_c L; \tag{17}$$

$$\begin{aligned} E[D] =& (1 - PER_r) E[D_1] + PER_r P_{coop} E[D_2] \\ &+ PER_r (1 - P_{coop}) E[D_3]; \end{aligned} \tag{18}$$

where L is the payload length in bits; $E[D_1]$, $E[D_2]$ and $E[D_3]$ are the corresponding expected lengths of the virtual time slot when the direct transmission succeeds, the direct transmission fails with cooperative retransmission, and the direct transmission fails without available cooperative relays, respectively. They can be calculated as:

$$E[D_1] = E[\delta] + T_{DATA} + T_{ACK} + SIFS + DIFS; \tag{19}$$

$$E[D_2] = E[D_1] + T_{DATA} + T_{ACK} + E[T_b] + SIFS; \tag{20}$$

$$E[D_3] = E[D_1] + DIFS; \tag{21}$$

where T_{DATA} and T_{ACK} are the transmission time for the DATA and ACK packets, respectively; δ is the consumed backoff time before each packet transmission. $E[T_b]$ is the expected backoff time the relay node with the best relay channel quality used before its transmission, and can be calculated as:

$$E[T_b] = \sum_{j=1}^{m} P\left\{\gamma_1 \in [\vartheta_j, \vartheta_{j-1})\right\} j \cdot slottime, \tag{22}$$

where,

$$\begin{aligned} &P\left\{\gamma_1 \in [\vartheta_j, \vartheta_{j-1})\right\} \\ &= P\left\{\gamma_1 < \vartheta_{j-1})\right\} - P\left\{\gamma_1 < \vartheta_j)\right\} \\ &= \left(1 - e^{-C\vartheta_{j-1}}\right)^M - \left(1 - e^{-C\vartheta_j}\right)^M . \end{aligned} \tag{23}$$

Finally, the throughput of the cooperative retransmission scheme, η, can be obtained by taking Eqs. (19) $\sim$ (22) into Eq. (18), and then substituting Eqs. (17) and (18) into Eq. (16).

E. Optimization Statement

Based on the analysis in the preceding subsections, the average network throughput is dependent on the threshold values $\vartheta_j, j = 1, 2..., m$ with given noise power, $N_0 W$, the distance from S to D, d, number of relay nodes, N, and so on. With given relay topology in the network and channel conditions, the throughput can be expressed in a function of $\vartheta_j, j = 1, 2..., m$, and optimal values of ϑ_j should be derived to maximize the system throughput. The optimization problem can be shown as follows:

$$\begin{aligned} &\texttt{Maximize} \left\{\eta(\vartheta_j, m)\right\}, j = 1, 2, .., m-1 \\ &\texttt{subject to} : (\vartheta_{j+1} - \vartheta_j \ge 0, j = 1, 2, .., m-1) . \end{aligned} \tag{24}$$

As mentioned in Sec. III, the number of threshold values, m, is determined by the durations of (DIFS-SIFS) and slottime. In our study, we use 802.11g system as an example, and two parameters, ϑ_1 and ϑ_2, will to be tuned to optimize the network throughput.

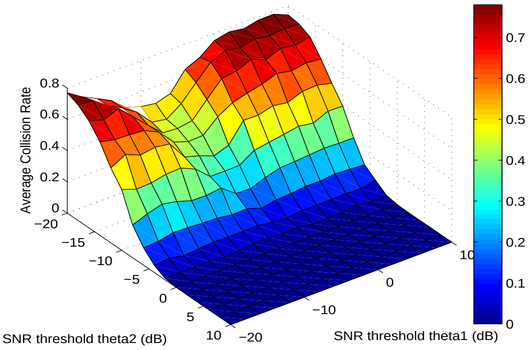

Fig. 3. Average Collision Rate with Different Threshold Values (E_b/N_0=0).

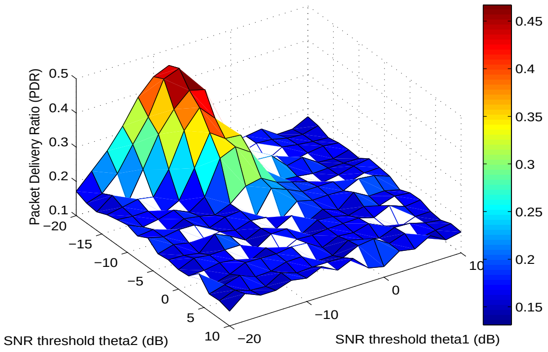

Fig. 4. PDR with Different Threshold Values (E_b/N_0=0).

V. SIMULATIONS AND NUMERICAL RESULTS

The simulation parameters are set up according to the 802.11g standard, as listed in Table II. S and D are placed 300 meters apart from each other. The relay nodes are placed randomly within a radius of 30 meters around the destination node. The channels between each transmission pair are implemented as independent Rayleigh fading channels. QPSK and Convolutional Code (CC) 1/2 is adopted, with the corresponding β_n, κ_n and γ_n^{th} from Eq. (5) as 7.2×10^3, 5.3, and 2.0 dB, respectively.

TABLE II
SIMULATION PARAMETERS.

MCS Scheme	QPSK/ CC 1/2	DATA length	500 Bytes
ACK length	14 Bytes	CFC length	14 Bytes
MPDU header	24 Bytes	DIFS	34 μs
PHY header	20 μs	SIFS	16 μs
Datarate	34 μs	Slottime	9 μs
Basic datarate	6 Mbps	CW_{min}	15

Fig. 3 and Fig. 4 illustrate the influence of different threshold values on the average collision rate among relays and the packet delivery ratio, respectively. It is obvious that the performance of the cooperative scheme with high density of relay nodes is highly affected by the different threshold values. The network performance can be improved significantly by reducing the collision probability through the optimal threshold values. The throughput improvement by using the optimized relay scheme compared with the original C-ARQ scheme under different channel conditions is shown in Fig. 5. The optimal values of the threshold SNR are obtained through the analysis in Sec. IV. It can be observed that the optimal relay scheme has shown significant advantage over the original DCF protocol in a dense network, while C-ARQ has no benefits from cooperative retransmission, due to the high collision probability.

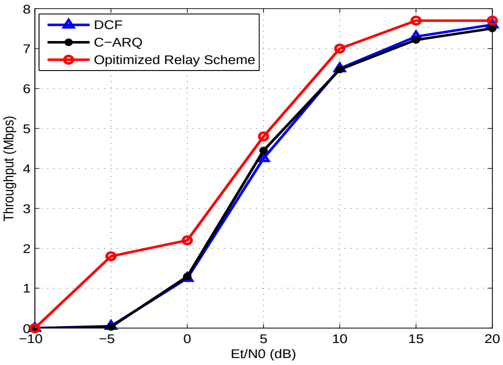

Fig. 5. Throughput Performance Comparision (SNR_{low}=2.0 dB).

VI. CONCLUSIONS

Collisions among different relay nodes can degrade the network performance remarkably in a cooperative network with high density of relay nodes. In this paper, we presented a complete analysis of the C-ARQ protocol performance with impairment resulting from collision. Thereby, an optimized relay selection scheme is proposed to maximize system throughput, which can also be adopted in other cooperative protocols with similar problems. The performance improvement by the proposed optimal relay scheme is verified by simulations.

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